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IMPACT RESPONSE OF AN ENERGY ABSORBING EARCUP

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For the past 12 years the U.S. Army Aeromedical Research Laboratory (USAARL) has been involved in an active program of evaluating the impact performance of aviator flight helmets retrieved from aviation accidents. From these evaluations, it has become evident that the current army flight helmet, the Sound Protective Helmet Number Four (SPH-4) (2), is relatively deficient in its ability to protect wearers against impacts to the lateral portions of the helmet (3,6). This is felt to be due to the fact that there is essentially no energy absorbing material interposed between the helmet shell and the hard plastic circumaural housing for the communications headphones. There is a foam liner incorporated into the superior portions of the helmet, but it does not generally extend below the "hatband" region of the head at the sides of the helmet. Consequently, the force of an impact directed at the earcup region of the helmet is transmitted to the head of the wearer with relatively little attenuation other than that provided by the load spreading effect of the helmet shell itself. Accident statistics indicate that 26% of all impacts to the SPH-4 have occurred in the earcup region, and impacts in the area are known to result in substantially more severe injury than impacts to other areas of the helmet (4). To provide increased impact protection to the earcup region of the helmet, a crushable energy-absorbing earcup was developed to be a direct replacement for the standard plastic earcup. The modified earcup is constructed of 1 mm (0.040 inch) thick aluminum and is designed to provide 25 mm of crush at a load of 4500 N. The crush distance was selected based on available space within the current helmet so modification of the helmet shell would not be required.

The load limit of 4500 N was arbitrarily selected based on what little data is available on human tolerance to impact in the temporo-parietal area of the skull (4,5,7). This load level is admittedly relatively high, being close to fracture threshold for localized impacts in the temporo-parietal area (5,7). However, the size of the earcup allows loads to be spread over a large surface area (7900 mm^2), and because of the limited stroke distance available, a relatively high load limit had to be used to provide protection for the maximum range of impact severities.

Acoustical testing of the energy-absorbing earcup has shown that it provides sound attenuating capability equivalent to that of the standard earcup. Initial impact tests were carried out utilizing a humanoid headform dropped onto a helmet-earcup segment in a standard impact of 92 N.m (70 ft-lb) (2) input energy. The energy absorbing earcup transmitted a peak load of 4500 N whereas peak loads for the standard earcup were five times that level.

Clearly the new energy absorbing earcup provides increased load attenuating capability over that of the current design. Nevertheless, since many assumptions were made in selecting the load limit for the earcup and since only isolated helmet segments had been impact tested, it was felt that helmeted cadaver impact tests would add useful information for validating the crushable earcup concept.

MATERIALS AND METHODS

The experimental design called for a whole-body drop test which would result in the impact of the helmeted head against a rigid surface. The rest of the body was to impact a cushioned surface so that the effect of body deceleration on head impact would be minimized. A photograph of the test apparatus is shown in Figure 1. The rigid impact surface consisted of a compression type load cell 150 mm in diameter (Denton, Inc.), supported by a rigid steel frame. A canvas sling was utilized to hoist the helmeted subject to the desired drop height and to maintain proper body orientation prior to the drop. The subject was oriented with its sagittal plane parallel to the horizontal and its head and neck projecting from the sling (Fig. 1). The head was placed in proper orientation with duct tape attached between the helmet and the frame of the suspension sling. The load cell frame was positioned to insure contact of the earcup portion of the helmet with the center of the load cell. A 200 mm thick foam mattress supported by a wire mesh frame was used to cushion the body upon impact. The height of the mattress was adjustable to permit the body to contact the mattress at or just before the time of head impact. The sling was suspended from a pulley system that allowed the drop height to be adjusted up to 3 meters. The test subject and sling were released by a solenoid controlled release mechanism.

Cadavers used in these tests were instrumented with a triaxial accelerometer cluster made up of Endevco Model #2264 accelerometers. The accelerometer mount was firmly attached to the frontal aspect of the maxilla with bone screws. The sensitive axes of the accelerometer were oriented along the posterior-anterior (x-) direction, the right-left (y-) direction and the inferior-superior (z-) direction. The impact was recorded on high speed film (400 fps) using a single camera placed in front of the impact assembly. Load cell and acceleration data were recorded on analog tape and filtered at 1000 Hz. prior to digitization at 4000 Hz.

Embalmed cadavers were selected for these experiments based on age, anthropometry and medical history. All subjects were less than 65 years of age, had no history of cancer or other prolonged debilitating diseases, and no previous history of skull or cervical fracture or surgery. Excessive obesity and craniometric measurements that did not correspond to available helmet sizes were reasons for rejection of a specimen. All potential cadavers underwent pre-impact radiological examination of the head and neck. Evidence of pre-existing fractures, marked structural abnormalities, or excessive osteoporosis were grounds for rejection of the cadaver.

Post-impact radiological examination of the head and neck was performed prior to autopsy. During the autopsy detailed external and internal crainiometric measurements were made. The skull was opened by removal of the calvarium, and the brain and dura excised to expose the inner surface of the skull to determine if any fractures had occurred. The skull was then separated from the neck at the atlanto-occipital junction and stripped of all coverings in order to examine the external surfaces for fracture.

The experimental apparatus was tested utilizing a DOT Part 572 50th percentile dummy prior to experimenting with cadavers. For these drops the method was identical to that described for the cadaver drops except that the triaxial accelerometer was mounted in the head of the dummy.

RESULTS

Twelve cadaver impacts were performed. Six cadavers were fitted with SPH-4 helmets equipped with standard earcups and 6 were fitted with helmets equipped with energy absorbing earcups. Additionally, 3 dummy impacts were performed for purposes of validating the test method. The drop height was varied from 1.17 m up to 2.03 m. Table 1 is a summary of pertinent anthropometric data for the cadavers and the drop heights used for each of the 15 tests. There were no skull fractures in any of the cadaver drops. The only significant injury seen was a 45 mm curvilinear laceration in the scalp of the cadaver used in Test 005. The injury corresponded to the superior border of the standard plastic earcup used in that test. There were no lacerations on any of the cadavers fitted with energy-absorbing earcups.

Table II summarizes the average peak forces and peak head x-, y-, and z- accelerations measured for the standard and the energy-absorbing earcup tests. Table III shows the results of a t-test on unpaired samples, performed on test data obtained from the 7 cadaver tests at a drop height of 2.03 m. It can be seen that the average load for the energy-absorbing earcup at 2.03 m was over 45% less than that measured for the standard earcup ($p < 0.05$). Likewise the average head y-axis peak acceleration was 35% less ($p < 0.05$) for the energy-absorbing earcup drops. There was no significant difference for peak head accelerations in the x- and z- directions. Figures 2, 3 and 4 show a comparison of plots of load, head y-axis acceleration, and calculated resultant head acceleration for Tests 011 and 012. These data typify the differences seen between tests utilizing the two different earcup designs.

Figure 5 is a photograph of the helmet impacted in Test 009. It is representative of the damage sustained by most of the helmets used in these tests. Note the scuffing and the horizontal fracture through the right earcup region of the helmet shell. Figure 6 shows the two energy absorbing earcups used in this test. As expected, the left earcup was undamaged. The right earcup reveals the unsymmetrical nature of the loading it received during impact as most of the crushing is confined to the superior half of the earcup. The average compression was 6.9 mm or 28% of the available 25 mm. For purposes of comparison Figure 7 is a photograph of the standard earcup removed from the impacted side of the helmet used in Test 013. There is minimal damage to this earcup consisting of a hairline fracture of the flange along the superior border of the earcup (see arrow). This was the maximum damage sustained by any of the standard earcups used in the cadaver impacts.

Table IV is a summary of the measured compression for each of the energy-absorbing earcups used in this study. Since most of the earcups were not symmetrically loaded, a means of measuring average compression was developed. The point with the greatest compression and the point with the least compression were identified and a line drawn through them on the back of the earcup. A line perpendicular to this line passing through the center of the earcup was then drawn. Four measurements of height were then taken where the lines crossed the edges of the earcup. These heights were averaged and compared to the height of an undamaged earcup. This was the average loss in height or average permanent crush. This was compared to the total compression available (25 mm) and reported in Table IV as a percentage of crush available. Note that the greatest permanent compression seen was 53%. However, based on the elasticity of aluminum, it is probable that the maximum compression depth was 8-12 percent greater, or 61-66%.

DISCUSSION

In this series of blunt impacts to the earcup region of the helmet shell, peak loads and peak y-axis accelerations were considerably less for those subjects wearing SPH-4 helmets equipped with the energy-absorbing earcup than for those wearing helmets equipped with the standard plastic earcup. Although the difference in loads between the two earcups was significant, it was considerably less than expected based on the results of previous impact tests performed with metal headforms. In the helmeted cadaver impacts, there was only an average 45% reduction in peak loads for the energy-absorbing earcup as compared to loads measured for the standard earcup while the metal headform tests showed a 5-fold reduction at roughly equivalent input energies (4). There are several reasons for these discrepant results. In the headform tests a metal headform was dropped vertically onto the earcup section of helmet shell with the earcup resting directly on the load cell. The entire load was transmitted directly through the shell to the earcup and the system was not free to rotate or translate. In the helmeted cadaver impacts, on the other hand, the impact force was transmitted to the head not only through the earcup, but also through several points in the helmet shell and through the foam liner over the superior portion of the impacted side. These factors tended to reduce the loads delivered to the earcups during the cadaver impacts. This situation reduced the difference in measured performance between the two earcup designs when compared to the metal headform drops since it aids the performance of the standard earcup and prevents the energy-absorbing earcup from realizing its full crush capacity for the input energy used in these tests. At higher input energies, the difference in loads would be expected to become greater as the crushable earcup continued to limit the loads to the same approximate level seen in these experiments until it reached full crush. On the other hand, the rigid earcup would transmit increasingly higher loads as the input energy increased. Of course, this difference in measured loads between the two earcup designs in helmeted cadaver impacts would probably never attain the magnitude seen in the rather idealized metal headform tests for the reasons enumerated above.

One major problem encountered in this study relates to the utilization of embalmed cadavers. Embalmed specimens were used since they were much more available than fresh cadavers. However, after embalming the subcutaneous tissue in the scalp becomes engorged with embalming fluid and swells considerably. Whereas the thickness of the skin in the posterior auricular area in the live subject is normally only 2-3 mm, many of the cadavers used in this study had thicknesses approaching 15 mm. This situation is reflected by the preponderance of extremely large head circumferences seen in the cadavers used in this study (Table I). Clearly this artifactually increased subcutaneous tissue depth provides the embalmed cadaver with a very high degree of impact attenuation capability not present in a live subject. This explains in large part why the relatively high input energies used in these experiments (approximately 136 N.m or 100 ft-lb for the 2.03-m drops) failed to produce skull fracture in the standard earcup tests or to produce high levels of crush in the energy-absorbing earcup tests (Table IV). In all probability, if fresh cadavers had been used, the same drop heights would have produced markedly greater loads and accelerations for the standard earcup tests and higher levels of crushing in the energy-absorbing earcups.

This study failed to provide any definitive data on the adequacy of the stroke level or distance selected for the energy-absorbing earcup. The engorged subcutaneous tissue in the scalp of the cadavers used appears to be the primary reasons. There is no question that the energy-absorbing earcup offers significantly increased impact protection over the standard (rigid) earcup design, and this fact alone is probably sufficient to recommend its incorporation into all U.S. Army flight helmets. In the meantime, it is hoped that these experiments can be repeated, using fresh cadavers and perhaps a modified procedure to try to obtain more definitive data on the performance of the crushable earcup.

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Table 1 - Summary of Anthropometric Data and Drop Heights

Test #	Subject	age/sex	Ht(m)	Wt.(kg)	Head Circum. mm	Head Circum. %	Drop Ht(m)
001	Dummy	-	-	76.0	584	87	1.17
002	Dummy	-	-	76.0	584	87	1.17
003	Cadaver	58 F	1.630	84.0	603	>99	1.17
004	Cadaver	60 F	1.645	70.0	570	65	1.17
005	Cadaver	59 M	1.790	86.0	580	86	1.17
006	Cadaver	64 F	1.500	70.0	580	86	1.70
007	Cadaver	58 F	1.535	78.0	580	86	1.70
008	Dummy	-	-	76.0	584	87	2.03
009	Cadaver	66 M	1.770	77.5	610	> 99	2.03
010	Cadaver	66 F	1.555	75.3	610	>99	2.03
011	Cadaver	68 M	1.585	51.3	533	2	2.03
012	Cadaver	61 F	1.820	68.5	572	70	2.03
013	Cadaver	57 F	1.710	95.0	640	>99	2.03
014	Cadaver	56 F	*	56.0	585	92	2.03
015	Cadaver	59 F	1.585	79.0	610	>99	2.03

*Specimen was a lower extremities double amputee

Table II

EA vs Standard Earcup
2.03-m Drop Tests
Average Peak Values ± 1 S. D.

Parameter	Impact Force (N) y-axis	Head x-axis	Acceleration y-axis	(g) z-axis
EA Earcup	5995 ± 1256	37.8 ± 8.2	121.0 ± 22.7	50.3 ± 17.2
Std. Earcup	11039 ± 2971	73.0 ± 32.6	187.3 ± 43.9	52.3 ± 7.6

Table III

EA vs Standard Earcup
2.03-m Drop Tests

Results of Unpaired t-tests

Parameter	DF	t	p (%)
Impact Force	5	3.12	5 $<$ p $<$ 2.5
Head x-accel	5	2.14	10 $<$ p $<$ 5.0
Head y-accel	5	2.64	5 $<$ p $<$ 2.5
Head z-accel	5	0.19	p $>$ 50

Table IV

Measured Compression of Energy Absorbing Earcups

Test #	Subject	Drop Ht(m)	Avg. Deform. (mm)	% of Available Crush
001	Dummy	1.17	3.6	14
003	Cadaver	1.17	3.3	13
004	Cadaver	1.17	6.6	26
008	Dummy	2.03	11.4	46
009	Cadaver	2.03	6.9	28
010	Cadaver	2.03	9.4	38
011	Cadaver	2.03	12.7	51
015	Cadaver	2.03	13.2	53

Figure 1. Photograph of test apparatus

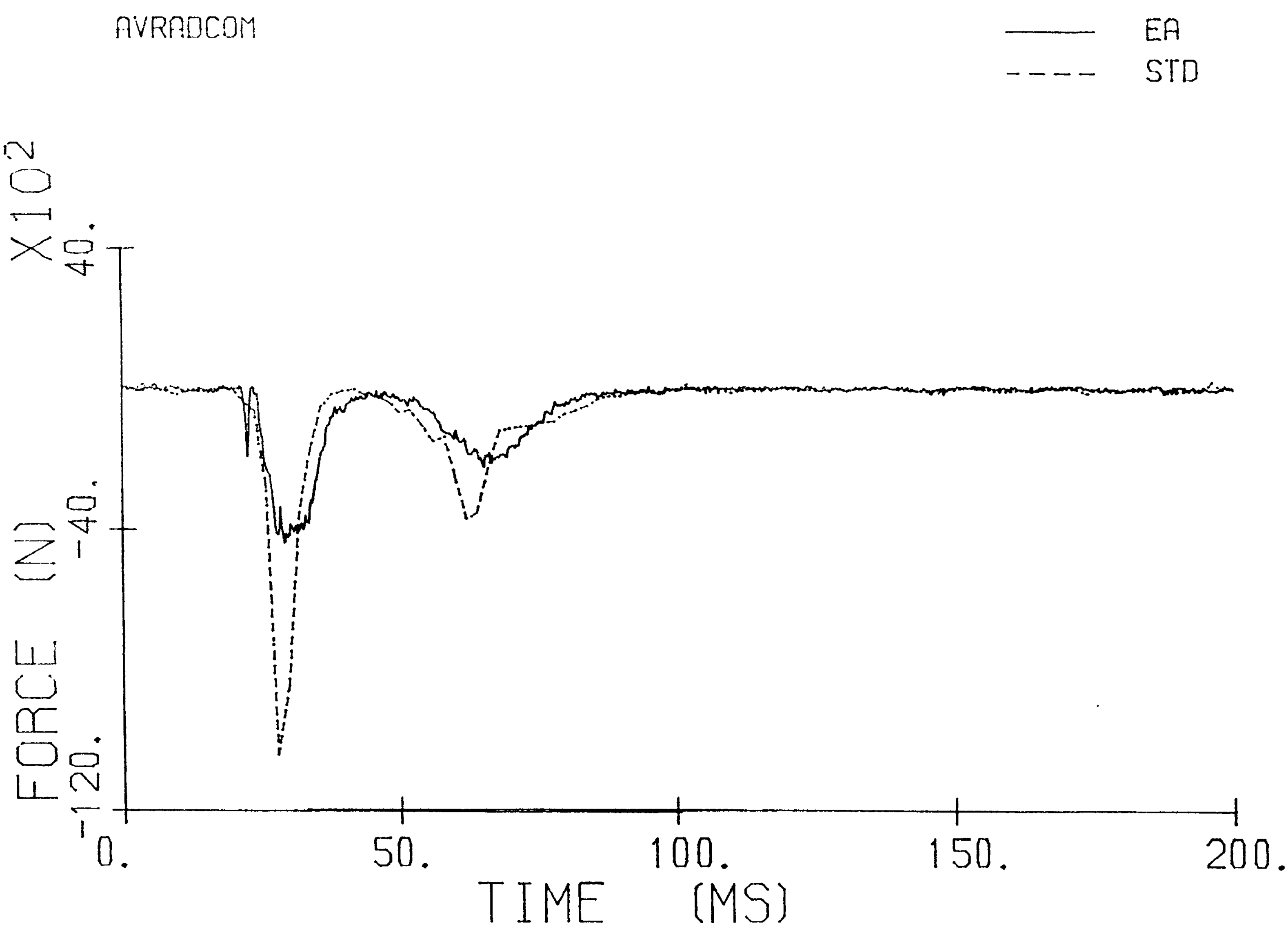

Figure 2. Comparison of force for EA and standard earcups

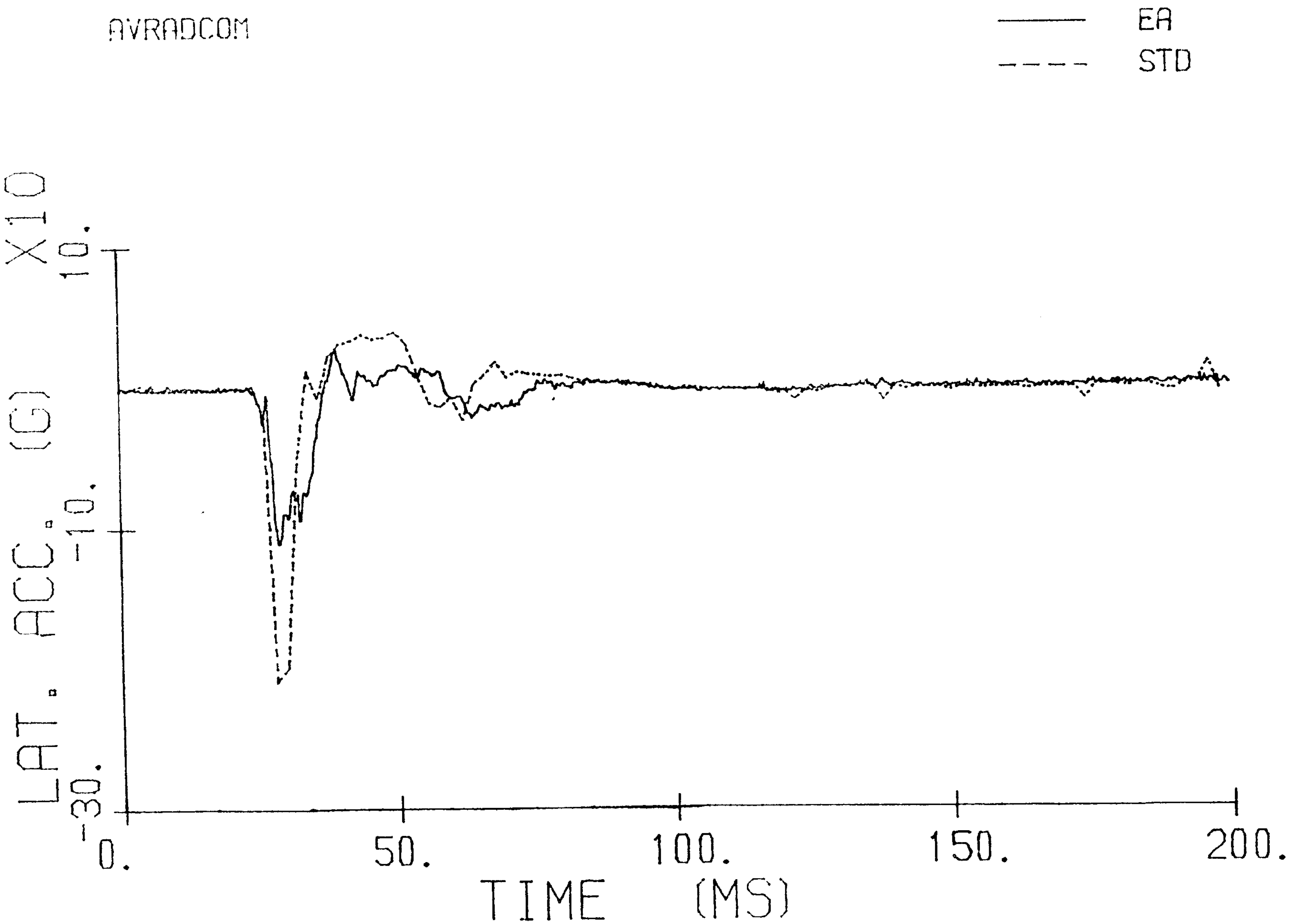

Figure 3. Comparison of head lateral (y-axis) acceleration for EA and standard earcups

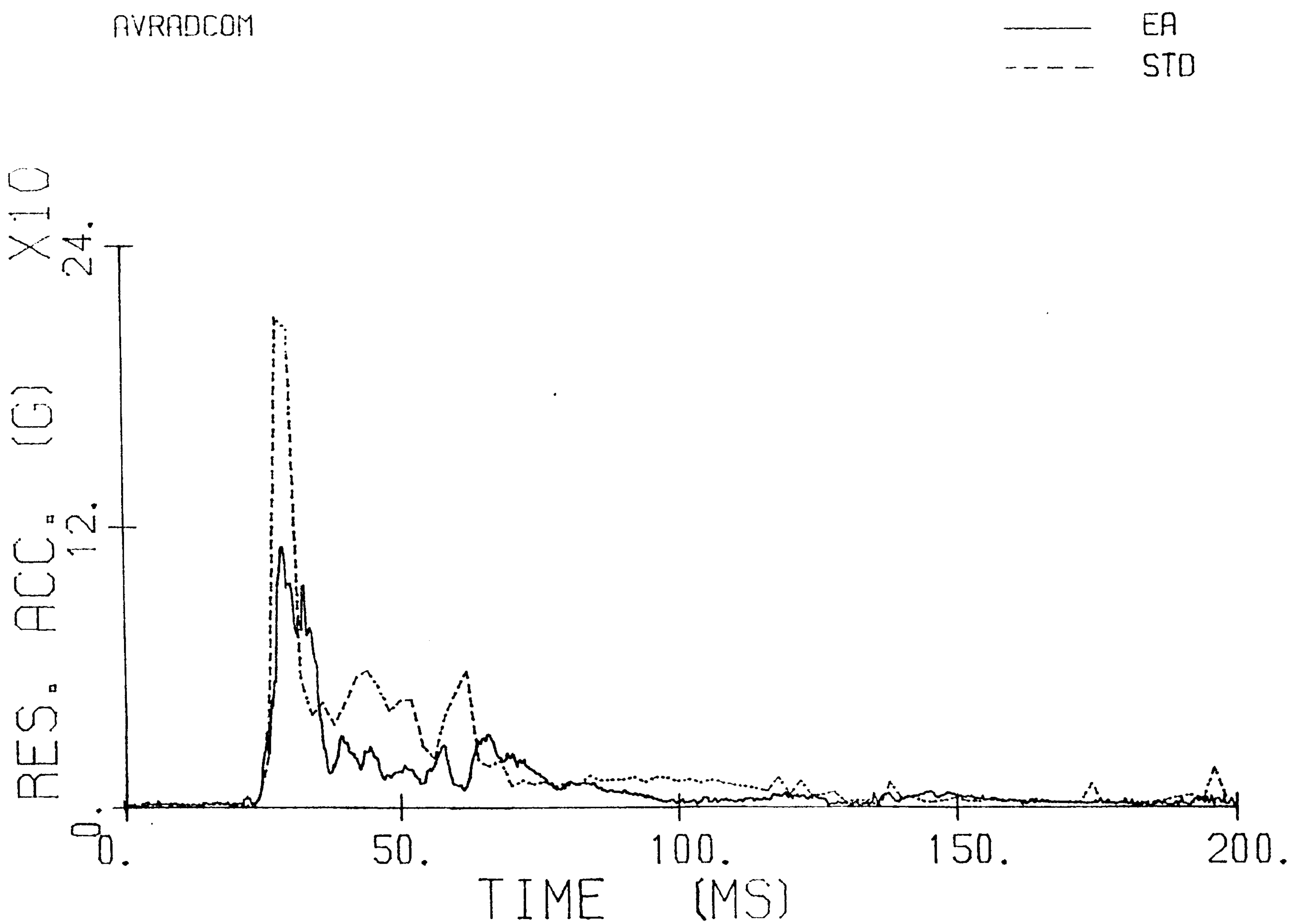

Figure 4. Comparison of resultant head acceleration for EA and standard earcups

Figure 5. Impacted helmet in Test 009

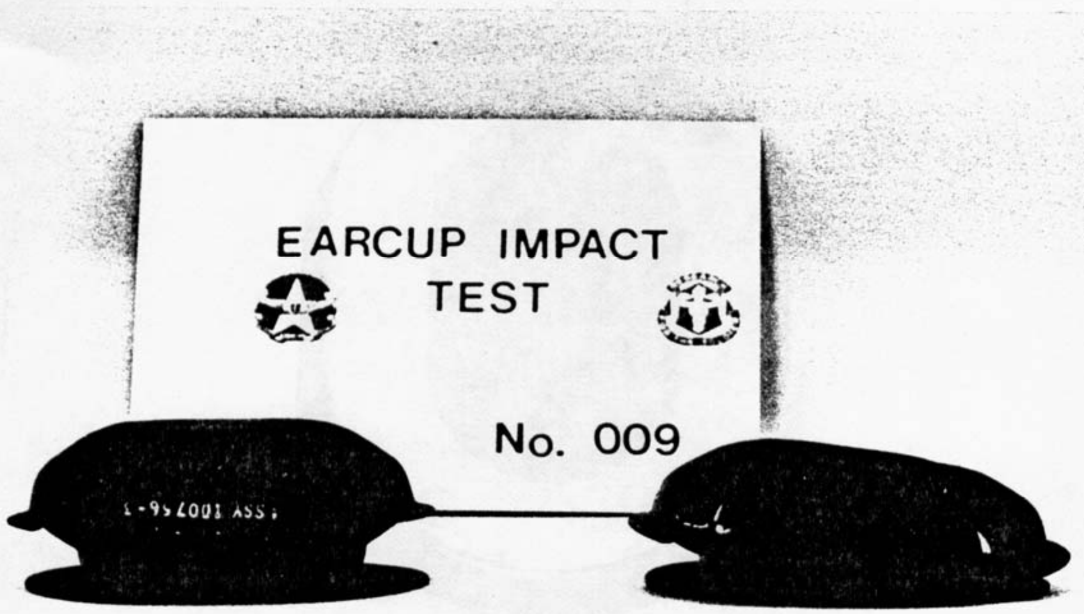

Figure 6. EA earcups used in Test 009

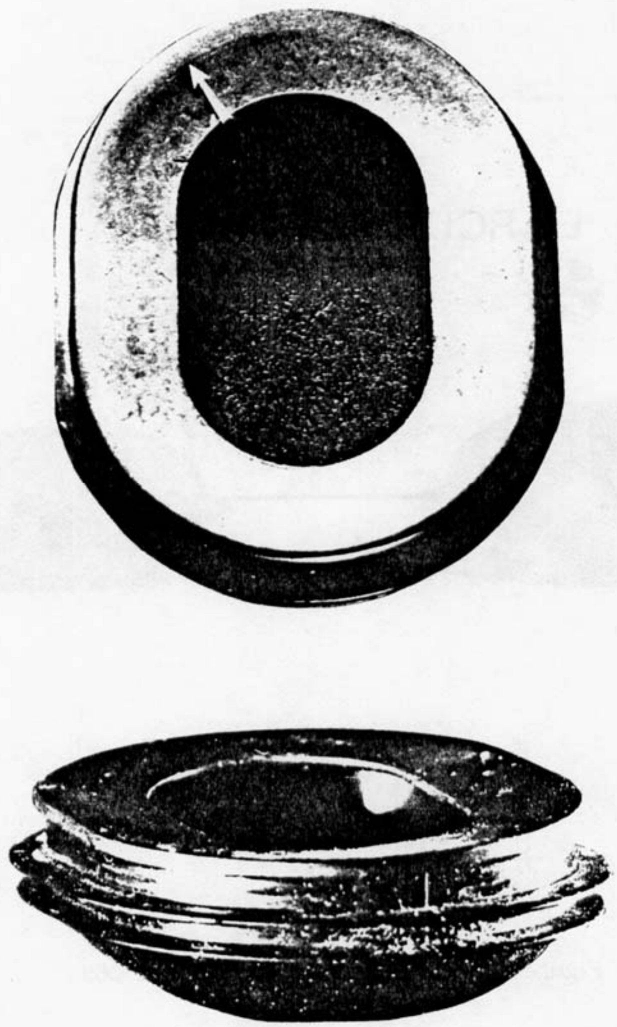

Figure 7. Standard earcup from the impacted helmet used in Test 013